*Indian J. Phys.* **76A** (2), 193-198 (2002)

**IJP A**
an international journal

# Field configuration and design of a new 14.4 GHz ECR ion source for the superconducting cyclotron under construction

M H Rashid*, D K Bose, C Mallik and R K Bhandari
Variable Energy Cyclotron Centre (DAE), Sector-1,
Block-AF, Salt Lake, Kolkata-700 064, India

E-mail : haroon@veccal.ernet.in

*Received 18 April 2001, accepted 11 December 2001*

**Abstract** : A new ECR ion source was designed by properly configuring the magnetic bottle long enough to confine a plasma of a desired heavy element for high charge state ion beams. The axial mirror-maxima of the magnetic field at the two ends were optimised for the first time by varying the angle of slant-surfaces of the iron plugs with the axis. The composite and absolute resultant static magnetic field due to the coils and the permanent magnet sextupole were evaluated.

**Keywords** : ECR ion source, magnetic mirror, multiply charged ions

**PACS Nos.** : 29.25.Lg, 52.50.Gj, 52.55.Jd

## 1. Introduction

The important function of the ECR ion source is to produce highly and multiply stripped positive heavy ion beams of various species by step-wise ionisation process. The strategy of multiple frequency heating, high mirror ratio and supply of cold electrons to the plasma, improves the performance of an ECR ion source [1]. It is wellknown that higher the magnetic mirror ratios of a magnetic trap, smaller are the losses of electrons from the plasma.

A high performance ion source will be needed for the superconducting cyclotron under construction than the presently working 6.4 GHz ion source [2] which was developed at this centre producing ions from gaseous stable elements for feeding the running K130 room temperature cyclotron. A room temperature ECR ion source (14.4 GHz) was designed for this. It is expected that the high charge state output current should be more than 200.0 eμAmp for $O^{6+}$, four times more than the existing one. It will produce not only highly charged ions of gases but also those of other solid samples efficiently.

The plasma confinement takes place in an inhomogeneous magnetic field on the principle of adiabatic invariance of the perpendicular magnetic moment of the electrons. For this reason there are two circular coils (400 Amps) on the two sides left and right to create tandem static axial magnetic mirror field. A sextupole magnet (3 north poles alternate with 3 south poles) of length 26.6 cm around the horizontal cylindrical surface will be placed between the two axial magnetic mirrors for creating the minimum *B* field in the plasma chamber.

## 2. Design goals

In the near future, there will be a great demand for high energy heavy ion beams of gaseous as well as metallic species from the K500 superconducting cyclotron under construction for research in the areas of atomic physics, nuclear physics *etc.* The cyclotron, working under various limits like bending limit, focusing limit *etc.*, will be capable of accelerating ions like $O^{8+}$, $Ne^{4+}$, $Ar^{13+}$, $Ar^{16+}$, $Kr^{23+}$, $Kr^{27+}$ *etc.* up to the possible high energy. The total transfer efficiency of the beam from a source after acceleration of the beam by the cyclotron on a target will vary from species to species and it is anticipated to be around 5% from the experience gained from the present K130 cyclotron and 6.4 GHz ECR ion source. The requirement of the beam current on the target may be about as high as 10 eμAmp of some species for irradiation purpose. Hence, we have the aim to get 200 eμAmp maximum intensity of the extracted beam of the kind of the species mentioned earlier from the ion source. The success of the high field operation of ECRs at other places, U-AECR at LBL [3], points in the most promising direction and generation of proper

* Corresponding Author

magnetic field configuration is very crucial for the 14.4 GHz microwave heating. So, we decided to have about $2B_{ECR}$ magnetic field at the cylindrical surface and the injection ends of the plasma chamber and slightly less than this value at the extraction end.

## 3. The magnet system

The magnet system is the base of the ECR source of multicharged ions. The magnet system serves two purposes, plasma confinement and electron cyclotron resonance heating. The high $B$ mode provides the main idea for the design of high confinement ECR ion source. The increase of the magnetic field affects not only the mean electron temperature and the ion confinement time, but also the electron density. The magnet was designed to meet the specifications and requirements set by the goals earlier. The main parameters of the magnet system are tabulated in Table 1.

the ultimate minimum field. The cylindrical co-ordinate system and appropriate symmetry was used to calculate the axial field using the 2D field calculator, POISSON [4] code due to the coils

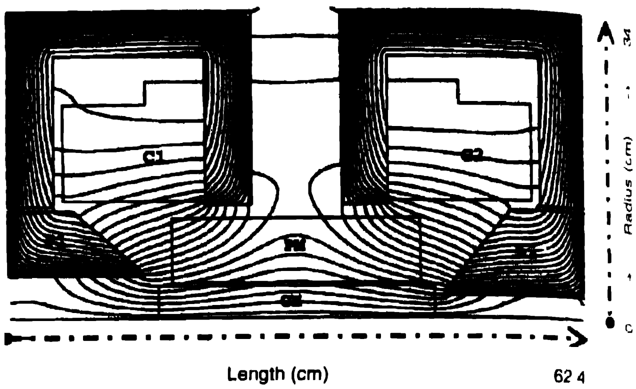


**Figure 1.** Geometry of the magnet system with the plot of lines of force due to the coils

**Table 1.** Parameters of the magnet system of the recently designed 14 4 Ghz ECR ion source.

| | Sextupole | Coils (2 Nos such) | Plasma chamber | |
|---|---|---|---|---|
| 2IR - I D (cm) | 7 60 | 25 00 | 6 96 | 1.0 mm gap |
| 2OR = OD (cm) | 22 00 | 57 60 | 7 56 | in between |
| Length (cm) | 26 60 | 16 4 each 19 6 apart | 26 60 | |
| Calculated mag field (kG) | 11 5 (at the vicinity of the inner surface of the chamber) | 12.0 (injection end) 9 45 (extraction end) 3 2 (at the centre) | | |
| Power dissipation (kW) | | 1 68/pancake (electrical power), 9 such pancakes | 1 00 (assumed on the inner chamber wall) | |
| L C W flow (l/min) | | 1 55 at 125 PSI water pressure | 0 3 at 200 PSI water pressure | |
| Temp rise (°C) | | ~ 15 | ~ 3.2 | |

### 3.1 *Coils and axial magnetic field :*

The axial field is generated by two solenoid coils made up of 8 mm square copper conductor with a 4 mm diameter central hole for water cooling. The conductor will be wrapped with insulation tape and vacuum impregnation. Each coil consists of 9 pancakes and about 1,20,000 ampere turns is needed to produce an axial mirror field of about 11 kG. The two coils are separately enclosed in a low carbon ferromagnetic 1010 steel yoke of 5.0 cm thickness and the field anywhere in the yoke does not exceed the saturation value 21.0 kG. The value of the minimum field at the centre of the plasma chamber length is strongly dependent on the position of the yokes at the centre. The wider the centre gap between the yokes the lower is the centre field. The low ampere-turn became possible as a result of a specially optimised design of the iron plugs at the two ends of the source. It is also worth mentioning that we got an optimised minimum axial magnetic field at the centre (at the centre position of the plasma) of the source to be about 3.2 kG. The fields at the chamber ends deplete more in an attempt to get the lower minimum-$B$ than 3.2 kG by means of either reducing coil current or increasing the gap in between the coils and reduces the mirror ratios, so the designed value is now

The plot of the lines of force with geometrical dimension is shown in Figure 1. It shows, how the iron plugs on the ends concentrate the lines of force at the chamber-ends. The plot of axial field ($B_{coil}$) on the axis (at $r = 0$) as well as at the vicinity of the chamber cylindrical surface (at $r = 3.46$ cm), along the length is shown in Figure 2. The position of the plasma chamber is also

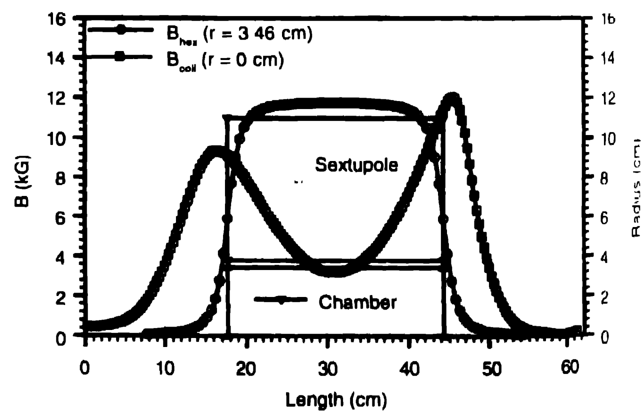


**Figure 2.** The sextupole field ($B_{hex}$) for remanence 11.6 kG and coil field ($B_{coil}$) at radius 0.0 and 3.46 is plotted. The positions of the sextupole magnet and chamber are also shown.

shown to assess the relative position of the axial magnetic field peaks. The origin for the plots has been taken at the meeting point of the $z$-axis and the outer yoke surface at the extraction side.

Cooling calculations of the coil pancakes and the surface of the plasma chamber were done [5]. It was found that the maximum rise in temperature is ~ 15 °C due to dissipation of 1.68 kW of power in each of the pancakes and ~ 3.2 °C due to assumed absorption of ~ 1 kW power on the wall of the chamber for obtaining the designed field configuration at the inlet pressure indicated in table 1 of low conductivity water. So the working ambient temperature of the coils is expected to be ~ 40°C and much below it for the chamber.

*3.2 Sextupole and radial magnetic field :*

The radial magnetic field is produced by a Halbach [6] type of sextupole structure made of Neodymium-Iron-Boron (Nd-Fe-B) which does not need any yoke. The permanent sextupole magnet is made up of 24 trapezoidal segments, where the angle of magnetisation varies by 60° from one segment to the next, enclosed in a nonmagnetic cylindrical casing made of stainless steel having magnetisation vector $\boldsymbol{M}$ in the plane perpendicular to the longitudinal axis. The sextupole will be placed in between the magnetic mirrors created by the coils. The axial field component will not affect the permanent magnet material as the axial field is perpendicular to the easy axis in the blocks, but the radial field component will add up to the de-magnetising field in some of the blocks. The permanent magnet material chosen has the intrinsic coercivity of 1.84 MA/m and should offer sufficient safety against de-magnetisation. The maximum radial demagnetising field due to the coils at the position of the permanent magnet blocks was found to be 0.60 MA/m. To be on the safer side, we used 1.06 MA/m coercive force for the field calculation due to the permanent magnet blocks. The material has maximum remanence of 12.0 kG and used 11.6 kG for actual field calculation by PANDIRA code. Only one-sixth of the azimuthal geometry of the sextupole was used in the field calculation in a rectangular co-ordinate system due to symmetry. It creates radial magnetic flux density of 11.5 kG at 6.92 cm diameter at the inner surface of the plasma chamber wall. The plot of the

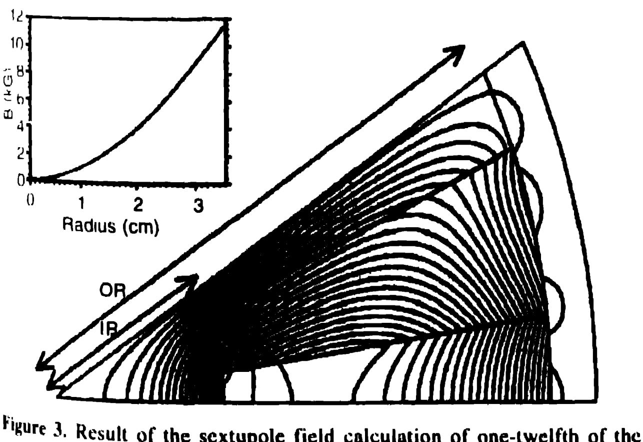


Figure 3. Result of the sextupole field calculation of one-twelfth of the whole azimuth The plot of lines of force and field with radius as an inset

radial field at the centre of the sextupole length with radius is shown in Figure 3. The field due to the sextupole ($B_{hex}$) also at the vicinity of the plasma chamber (at $r = 3.46$ cm) is shown in the Figure 2 along the length taking into account the end effect of the sextupole.

First the field of the sextupole magnet was calculated using the PANDIRA code and end effect of the sextupole was calculated with the help of the TrapCAD code by feeding the Pandira output data. The TrapCAD code uses the following procedure to calculate the end effect of the sextupole. The radial component of the stray field is written as

$$B_r(r,\phi,z) = B_{rp}(r,\phi)\cdot T(r,z), \tag{1}$$

where $B_{rp}$ is the output field data from the PANDIRA and $T(r, z)$ is the tapering function which is given by the following semi-empirical formula

$$T(r\cdot z) = \frac{1}{2}\,\left(z^2 + p(r)^2\right)^{1/2} + 1 \tag{2}$$

$$p(r) = 2.4 - 1.6 - \tag{3}$$

The estimation of the parameter $p(r)$ was given by Vamosi and Biri [7] after studying some measured data and fed into the code to be used and $T(r, z)$ is used as an inbuilt optional tapering function in the code. The contribution to the off-axis axial field because of end effect is small due to the end effect. The end effect is calculated at $r = r_{max} = 3.46$ cm so value of $p(r)$ is 0.80. The design of the sextupole fulfils the specifications set by the goals and the effect of the radial field component from the magnetic mirrors has been taken into account in the choice of permanent magnet material having trade name VACODYME 396 HR which gets demagnetised a little due to heat at as high as 60°C. The working temperature may be about 40°C.

*3.3 Novel iron plugs :*

Plugs with flat inner surface were used till now. The iron plugs with surface slant to the $z$-axis making the inner surface thin is new to be used in the injection and extraction ends which enhance the axial magnetic field appreciably. The position of the maxima at an end on the chamber is decided and fixed largely by the position of a plug on the respective end. The angles subtended by the slant surface of the plugs with the axis was optimised for maximum axial field at the position of the peaks but minimum axial field at the centre. They increase the axial field at the inner surfaces of the chamber ends also. The optimised angle of the slant surface of the iron plugs at the extraction (P1) and injection (P2) end are 39.0° and 67.0° respectively for maximum field in the vicinity of the chamber ends. The plugs will not hinder the placement of the end flanges of the chamber, extraction electrodes, gas feeding lines, microwave injection line, chamber cooling lines, vacuum pipes, *etc*. because of sufficient space left for them.

### *3.4 Magnetic field analysis :*

The value of the magnetic field at the extraction end axis of the chamber is 9.45 kG. This corresponds to the highest magnetic closed surface in the chamber. The dimensions of the chamber are 26.6 cm long and 6.96 cm in diameter. It is seen that the value of the absolute field due to the coils varies slightly with radius at the extraction and mid-length but it is about constant at the injection end. The absolute field at the end-region only due to the permanent magnet sextupole also decreases outward with respect to the centre position from the calculated ones due to end effect. The drop in radial magnetic field becomes significant from about 2.5 cm inside the ends of the plasma chamber. This field at the end-region along the length was calculated with help of TrapCAD by using the built in tapering function incorporated in it. The size and position of the plasma corresponds to the iso-Gauss field surface at resonance field (5.143 kG) corresponding to the 14.4 GHz microwave frequency.

It is interesting to evaluate the combined field due to the coils and the sextupole also. The two field were superimposed component wise at several grid points. First, it was evaluated at the vicinity of the cylindrical surface taking into acount the end effect of the sextupole at grid points formed by azimuths from 30° to 90° at the interval of 5° and from 16.2 to 45.8 cm along the length at the interval of 1.0 cm The field is plotted in Figure 4a It is clear at the injection end that there is a small dip in field because the sextupole is shorter than the plasma chamber in length but it is not a cause of concern as it is well above the $2B_{ECR}$ value and the plasma is well within the bounds of the chamber. Similarly, the composite field has been evaluated at the ends of the chamber at the grid points formed by radius from 0.26 to 3.46 cm at the interval of 0.6 cm and the same earlier azimuths. The fields at the extraction and injection ends are plotted in Figure 4(b) and 4(c) respectively. This evaluation was done for azimuth from 30° to 90° only because the fields from 30° to 0° and from 30° to 60° are the same in order and magnitude and also the fields from 90° to 60° and from 90° to 120° are the same in order and magnitude.

## 4. The resonance zone characteristics

The region of an absolute magnetic field, in which electrons gyrate around the lines of force in a plane perpendicular to it with the frequency of microwave thrust in, is called the resonance zone. Transfer of energy from the microwave to the electron takes place in the vicinity of this region of resonance zone only. This is basically an enclosed iso-Gauss surface of the absolute magnetic field around the centre of the chamber corresponding to the *rf* frequency.

If the field is non-uniform, the field lines generally are curved. The electrons drift rapidly along a slightly curved line of force spiralling around it because of nonuniformity of field across it and drift slowly perpendicular to it because of its curvature. It is seen by simulation that in the presence of an axial field or a

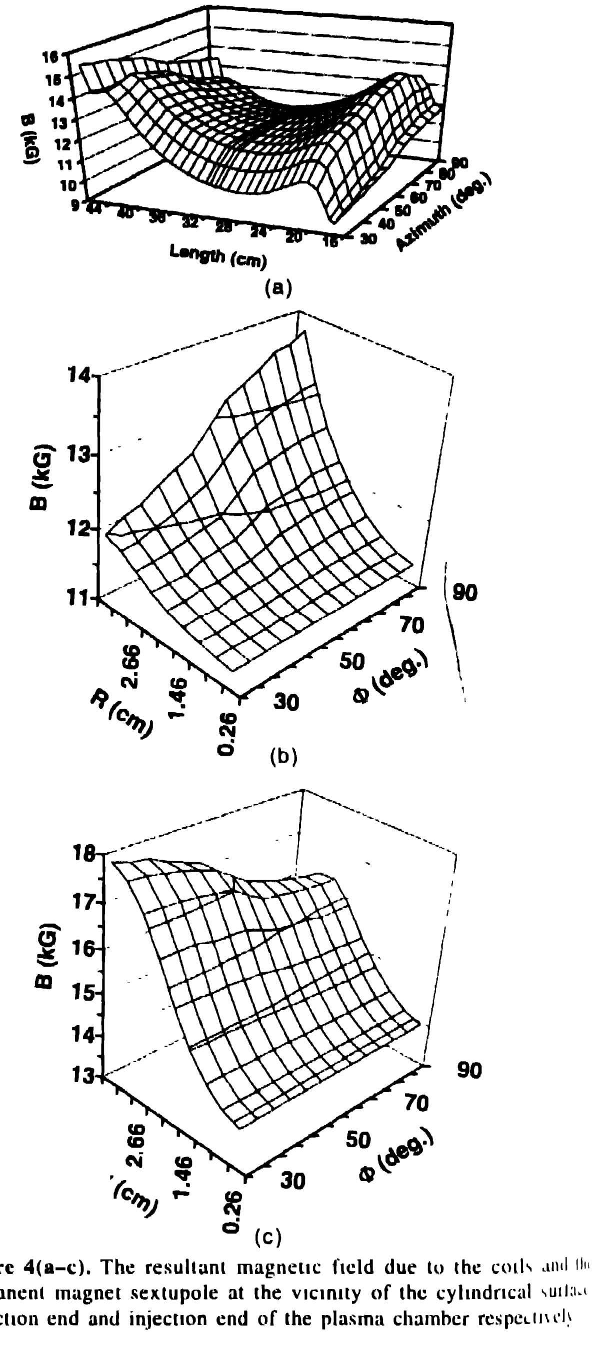


**Figure 4(a–c).** The resultant magnetic field due to the coils and the permanent magnet sextupole at the vicinity of the cylindrical surface extraction end and injection end of the plasma chamber respectively

radial field the electrons drift slowly in azimuthal direction or in longitudinal direction in the chamber. The overall drift velocity vector in the composite magnetic field $B$ in current free space with random orientation of the momentum vector is written as [8]:

$$u = \frac{1}{2m^2\omega_c B}\left(p_\perp^2 + 2p_\parallel^2\right)\left(\hat{b}\,|\,\text{grad } B\,|\right),$$

where $\hat{b}$ is the unit vector along $B$ vector, $p_\perp$ and $p_\parallel$ are the perpendicular and parallel components of the electron momentum with reference to the lines of force and $\omega_c$ and $m$ are the cyclotron frequency and electron mass respectively.

But this drift becomes very complex in presence of the ECR plasma which is held in restraint by switching on both the axial and the radial field. In spite of electrons being vigorously affected by thermal gradient and highly statistical random collisions, they follow one or the other lines of force due to the presence of magnetic field and this is the situation in which the mirror effect of the field come into play.

## 5. Source description

The schematic diagram of the source is shown in Figure 5. The source is enclosed in iron yokes Y1 and Y2 of thickness 5 cm enclosing the coils C1 and C2 respectively. Overall length and diameter of the whole system are 62.4 and 68.0 cm respectively. The plasma chamber is made of double walled nonmagnetic stainless steel. In between the walls, there are water circuits for cooling the plasma chamber. The length and inner diameter of the plasma chamber are 26.6 and 6.96 cm respectively. The shaped iron plugs P1 and P2 have been used in the extraction and injection side for field intensification. Those two iron plugs are kept in position by bolting arrangements with teflon insulators. The microwave power will be fed through rectangular wave guide from the injection side. A positive high voltage upto 20 kV will be applied to the source while the puller electrode will be at ground potential initially. Reliable high performance power supplies will be used for biasing the system. One single insulator, indicated by a line in between the sextupole and coils, will be used to insulate the coil part from the source and the sextupole. The puller electrode E will be supported to the end flange of the source. Ion emission electrode (plasma electrode P) is made of aluminium and has 1.2 cm diameter aperture for beam extraction. One more thin aluminium sheet (F) of 0.05 cm thickness and 7.0

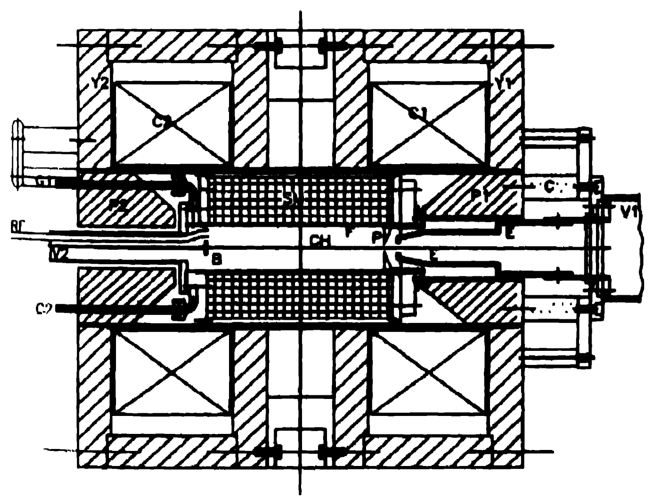


Figure 5. The schematic diagram of the ECR ion source. C1 and C2-Coils, Y1 and Y2-Iron yokes, P1 and P2-Iron plugs, V1 and V2- Vacuum ports, G1 and G2- Gas inlets, RF-Microwave feedings, SM-NdFeB Sextupole (hexapole) magnet, CH- Nonmagnetic steel plasma chamber, P-Al plasma electrode, F-Al sheet, B- Al based probe, E-Steel extractor and C- Ceramic insulator

cm length will be fitted on the plasma chamber wall near the extraction side to improve electron injection near the extraction zone. The distance between the puller and plasma electrode initially at 3.0 cm can be adjusted after breaking the vacuum. The turbo molecular pumps 53 l/s and 500 l/s will be in the injection and extraction side respectively. The system will be evacuated and maintained at a low pressure $10^{-6} - 10^{-7}$ torr with the desired gas or vapour to restrict charge exchange loss of highly charged ions with neutrals. An aluminium plate B shown on the injection end of the plasma chamber will be biased to act as a bias probe for injecting cold electrons into the plasma.

## 6. Discussion

The plasma density is limited by the applied *rf* frequency as electrons per cubic centimetre is given by $f_{rf}^2$ (kHz)/8.98. At higher frequency there is benefit of getting higher $n_e$ (electron density). So, one gets higher output current or high charge states according to the charge neutrality condition $e\sum_i Z_i < n_i > = e < n_e >$ of the plasma where Z and $<n_i>$ are the charge number and the average density of the ion of type $i$. So, as high as 14.4 GHz ($f_{rf}$(GHz) = 2.8 B(kG)) *rf* heating will be used. The 14.4 GHz microwave generators have the advantage that they are commercially available. At this frequency, the sextupole must be made of magnet which has high remanence ($B_{re}$ about 11.6 kG); accordingly the field configuration was designed to have more than $2B_{ECR}$ field on the chamber wall except at the extraction region for ease in extraction of the ions. Production of the most of the electrons take place at the vicinity of the resonance surface *i.e.* where the local mirror ratio is about 2 and hot electrons have high probability of getting reflected several times before falling inside the loss cone as a result of collisions and getting lost on the chamber walls. This crucial field configuration is essential for plasma stabilisation needed for high plasma confinement time which is closely related to the stepwise ionisation time. The cumulative effect of the high confinement time is the higher plasma density.

The hot electrons have very short confinement time and get lost very rapidly so it is important to have a good electron source. This in turn affects not only the mean electron temperature and the ion confinement time but also the electron density. The mirror ratio is more than 3.0 on the sides or cylindrical surface of the chamber and appreciably large plasma surface and volume were obtained. The magnetic field and particle simulation study by TrapCAD shows that the geometry of the confined plasma is sound and capable of generating high charge state ion beams because of enhanced heating and confinement of the plasma electrons.

The puller extracts ions from the nearest surface of the plasma and the extracted ions form a beam of mixed ions consisting of various charge states. The extracted current density (J) is proportional to $e\sum_i Z_i < n_i >< v_i >$ where $v_i$ and $n_i$ are the velocity and density of $i$ type of ions in the influence of the potential at the extraction region. So, the current of extracted beam depends strongly on the local plasma density or ion density

$n_i$ at the vicinity of the extraction electrode. The plasma electrode will be made of aluminium and a thin Al-foil will be tightly fitted on the plasma chamber wall at the extraction side so that the electrons flying off the plasma strike these and generate cold secondary electrons for increasing the electron density further in this region.

Fabrication work of the most of the components has been started. The winding of the coils will be completed very soon. Most of the power supplies are also under construction. The sextupole magnet will be received from M/S Danfysik very soon for mapping the field and subsequent installation. Microwave power (upto 2 kW) will be fed through rectangular wave guide. The position of the extractor electrode can be optimised for maximum beam. Even it can be replaced by a geometrically and functionally improved extractor later on.

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